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1 **Dominant flood generating mechanisms across the United States**

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12

13 **Journal** Geophysical Research Letters (*Hydrology and land surface studies*)

14

15 **Key Points**

16 1. Regional differences in mechanisms that control US flood timing and magnitude
17 are exposed

18 2. Disparity in timing and variability between floods and rainfall emphasizes the
19 importance of hydrological processes

20 3. Classification of dominant flood-generating mechanisms provides guidance to
21 flood studies

22

23 **Keywords** Flood; Hydro-climatology; Precipitation; Soil Moisture; Seasonality;
24 Snow

25

26 **Abstract**

27 River flooding can have severe societal, economic and environmental consequences.
28 However, limited understanding of the regional differences in flood-generating
29 mechanisms results in poorly understood historical flood trends and uncertain
30 predictions of future flood conditions. Through systematic data analyses of 420
31 catchments we expose the primary drivers of flooding across the contiguous United
32 States. This is achieved by exploring which flood-generating processes control the
33 seasonality and magnitude of maximum annual flows. The regional patterns of
34 seasonality and interannual variability of maximum annual flows are, in general,
35 poorly explained by rainfall characteristics alone. For most catchments soil-moisture
36 dependent precipitation excess, snowmelt, and rain-on-snow events are found to be
37 much better predictors of the flooding responses. The continental-scale classification
38 of dominant flood-generating processes we generate here emphasizes the disparity in
39 timing and variability between extreme rainfall and flooding, and can assist
40 predictions of flooding and flood risk within the continental US.

41

42 **1. Introduction**

43 Every year river flooding leads to fatalities [Ashley & Ashley, 2008; Di Baldassarre
44 et al., 2010] and multi-billion dollar damage [Jongman et al., 2012; Winsemius et al.,
45 2015], but floods also enhance ecosystem health and replenish reservoirs [Thomaz et
46 al., 2007; Richter & Thomas, 2007]. Although their significance for society is evident,
47 reliable estimation of flood hazard remains a challenge [Kundzewicz et al., 2014].
48 With an increased likelihood of high-intensity rainfall under a warming climate
49 [Trenberth et al., 2003; Allan & Soden, 2008; Min et al., 2011; Kendon et al., 2014],
50 the magnitude and frequency of floods are projected to increase [Milly et al., 2002;
51 Pall et al., 2011; Arnell & Gosling, 2014]. While increased precipitation extremes
52 have already been observed [Trenberth et al., 2003; Groisman et al., 2005; Allan &
53 Soden, 2008; Min et al., 2011; Westra et al., 2013], there is low confidence regarding
54 even the sign of trend in the magnitude of annual maximum floods (let alone exact
55 predictions), both globally [Kundzewicz et al., 2014] and in the US [Lins & Slack,
56 1999; Villarini et al., 2009, 2011; Hirsch & Ryberg, 2012].

57
58 Predictions of future floods and interpretation of historical flood trends are usually
59 based on statistical approaches using runoff- and sometimes precipitation-data [e.g.,
60 Gumbel, 1941; Cunnane, 1988; Lins & Slack, 1999; Villarini et al., 2009, 2011;
61 Villarini & Smith, 2010; Smith et al., 2015], or through the use of mechanistic models
62 describing precipitation partitioning at the scale of a river basin [e.g., Milly et al.,
63 2002; Te Linde et al., 2011; Arnell & Gosling, 2014]. The usefulness and reliability
64 of both methods are constrained by the degree to which they can represent the
65 relevant processes that control flood response. Hence, improved process
66 understanding is a key element for improving the prediction and interpretation of

67 flood trends [Merz and Blöschl, 2008a,b,c; Milly et al., 2008; Kundewicz et al., 2014;
68 Merz et al., 2014], especially under environmental change.

69

70 The need for process-based approaches for flood estimation catalyzed a wealth of
71 studies that acknowledge that factors other than rainfall may play an important role in
72 controlling floods [e.g., Merz et al., 1999; Merz & Blöschl, 2003; Sivapalan et al.,
73 2005; Bradshaw et al., 2007; McCabe et al., 2007; Parajka et al., 2010; Freudiger et
74 al., 2014; Slater et al., 2015]. Although these and many other studies emphasize the
75 importance of different flood controlling processes, understanding of the regional
76 differences in process controls of flooding responses is rather limited. Hirschboeck
77 [1991] hypothesize the meteorological mechanisms that cause floods, and discuss the
78 role of antecedent moisture and snow conditions. Villarini [2016] discusses which
79 meteorological patterns are important for flood seasonality. Yet, for the United States
80 there is no robustly tested continental-scale classification of regional differences in
81 the dominant flood- processes generating.

82

83 In this study, we assess the dominant flood-generating processes for 420 catchments
84 spread across the contiguous United States. We first explore the seasonality of floods
85 for all catchments and subsequently use that information to test hypotheses about the
86 underlying process controls, since the dominant flood-generating processes at a given
87 location can be strongly linked to the time of the year that major floods occur
88 [Hirschboeck, 1991; Merz et al., 1999; Merz & Blöschl, 2003; Sivapalan et al., 2005;
89 Parajka et al., 2010]. By comparing the seasonality of floods in the context of four
90 hypothesized flood-generating mechanisms, we explore which dominant processes
91 correspond to the observed seasonality of flooding in individual catchments. To

92 further clarify the role of these local runoff-generating mechanisms, we subsequently
93 explore which of the hypothesized flood-generating processes controls the observed
94 interannual variability in flood magnitude. Both flood characteristics have been
95 explored before for the United States [Hoyt & Langbein, 1955; Guo et al., 2014;
96 Villarini, 2016], but the hydrological processes that control both flood signatures have
97 not been uncovered. By combining understanding generated from examining the
98 controls on both the timing and magnitude of floods, we present an overview of the
99 regional differences in the inferred dominant flood-generating processes of all
100 catchments.

101

102 **2. Methods**

103 **2.1. Data**

104 We use daily streamflow and meteorological data for 420 MOPEX catchments for the
105 period 1948-2001 [Duan et al., 2006]. We eliminated 18 of the 438 catchments of the
106 original MOPEX dataset with less than 20 years of continuous data [Berghuijs et al.,
107 2014a]. The catchments range in size from 67 to 10,329 km² and were originally
108 characterized by limited human influence. Subsequent studies suggest that water
109 balances in these catchments can be impacted by agricultural activities [Wang &
110 Hejazi, 2011]. The seasonality of maximum annual flow (MAF) and of the
111 hypothesized flood-generating processes are expressed by the mean date of
112 occurrence ($\bar{\Phi}$) and the standard deviation of the mean date of occurrence (σ_{Φ}) using
113 circular statistics [Burn, 1997; Young et al., 2000]. In the Supplementary Material we
114 provide the computational details of $\bar{\Phi}$ and σ_{Φ} .

115

116 **2.2 Hypothesized flood-generating mechanisms**

117 Using a downward approach to hydrological prediction [Klemeš, 1983; Sivapalan et
118 al., 2003] we investigate which of four hypothesized flood-generating processes can
119 explain the timing and interannual variability of MAF. To assess the feasibility of
120 hypothesized flood-generating processes, we compare the $\bar{\Phi}$ -values of the MAF to
121 those of the four hypothesized mechanisms. Subsequently we test how much of the
122 interannual variability in MAF magnitude can be explained by the hypothesized
123 mechanisms. Rather than using complex models for exact prediction, our aim is to test
124 the first-order consistency of hypothesized processes and real-world observations.

125

126 *Hypothesis 1: flooding is caused by the single largest precipitation event:* streamflow
127 is assumed to be independent of the pre-event antecedent soil moisture storage, which
128 is controlled by seasonal rainfall, evaporation and drainage properties of the
129 landscape. Runoff generating mechanisms associated with such floods can be
130 infiltration excess overland flow [Horton, 1933]; preferential subsurface flow
131 [Šimůnek et al., 2003]; saturation excess overland flow; and fill and spill flow for
132 soils with storage capacities much smaller than total event precipitation [Dunne,
133 1978; Tromp-van Meerveld & McDonnell, 2006].

134

135 *Hypothesis 2: flooding is caused by the single largest series of precipitation events:*
136 The MAF is caused by multiple precipitation events during a several day period. The
137 period is set at 7 days, but analyses with periods ranging from 3 to 10 days yielded
138 comparable results. This hypothesis suggests that flooding is still independent of
139 evaporation controlled soil moisture conditions, but pre-event antecedent wetness
140 conditions and water storage play an important role for streamflow generation. Runoff
141 generating mechanisms associated with such floods can be saturation excess overland

142 flow [Dunne, 1978], and fill and spill mechanisms [Tromp-van Meerveld &
143 McDonnell, 2006].

144

145 *Hypothesis 3: flooding is caused by the single largest precipitation excess event; the*
146 MAF is caused by the largest precipitation excess event of the year. Precipitation
147 excess is defined as the rainfall excess compared to available soil moisture storage
148 capacity:

$$P_e(t) = \max(0, P(t) - (S_{u,\max} - S_u(t)))$$

149 where P_e is precipitation excess, P is the daily observed precipitation, S_u is storage in
150 the unsaturated zone, $S_{u,\max}$ is the soil moisture storage capacity according to the
151 bucket model of Milly [1994] at day t :

$$S_u(t) = S_u(t-1) + P(t) - P_e(t) - \min(0.75 \cdot E_p(t), S_u(t)).$$

152 Potential evaporation (E_p) is scaled to 75% of its daily value because not all E_p tends
153 to be used for evaporation. $S_{u,\max}$ is fixed at 125 mm as this on average corresponds to
154 root zone storage capacity of MOPEX catchments [Gao et al., 2014] and, on average,
155 simulates the long-term water balance within 1% of the observations (using this
156 simple bucket model). Hypothesis 3 suggests that antecedent soil moisture storage, as
157 controlled by seasonal rainfall and evaporation, is the primary control on runoff
158 generation in flood events. Similar to Hypothesis 2, the runoff generating mechanisms
159 associated with such floods can be saturation excess overland flow [Dunne, 1978] and
160 the fill and spill mechanism [Tromp-van Meerveld & McDonnell, 2006], but storage
161 is evaporation controlled.

162

163 *Hypothesis 4: flooding is caused by the single largest snowmelt or rain-on-snow*
164 *event: the MAF is generated by the largest snowmelt event or rain-on-snow event,*

165 where the snowmelt contribution is estimated according to a simple degree-day model
166 [Hock, 2003]:

$$P_{\text{snow}}(t) = \min(f_{\text{dd}} \cdot \max(T - T_{\text{crit}}(t), 0), S_{\text{snow}}(t)) + P(T(t) > T_{\text{crit}})$$

167 where P_{snow} is the snowmelt rate, P is the precipitation rate for days when the daily
168 average temperature T exceeds the temperature threshold T_{crit} set at 1 ($^{\circ}\text{C}$). f_{dd} is the
169 melt rate set at 2.0 (mm/d/K) [Woods, 2009], and S_{snow} is the snow storage:

$$S_{\text{snow}}(t) = S_{\text{snow}}(t - 1) + P(t(T(t) < 1) - P_{\text{snow}}(t)$$

170 Since there is no data available on snowmelt, snow storage, and rain-on-snow events,
171 the absolute value of P_{snow} is a rough approximation of snowmelt dynamics.

172

173 **4. Results**

174 **4.1 Seasonality of floods and flood predictors**

175 Results indicate the mean date ($\bar{\Phi}$) and variability of the date (σ_{Φ}) of MAF strongly
176 vary among the study sites (Fig. 1a). Broadly speaking, $\bar{\Phi}$ ranges from winter period
177 (western coastal states), to late winter and early spring (most eastern catchments, and
178 parts of California), to late spring and early summer (Great Plains, Mid West, Rocky
179 Mountains, Sierra Nevada, Northern Cascades), to late summer and autumn (New
180 Mexico). The variability of the mean day of MAF also shows strong regional patterns.
181 For catchments in the Rocky Mountains, and several coastal western catchments the
182 timing of MAF is very predictable. The central and eastern part of the United States
183 show regional differences in the degree of variability of the mean day of flood, with
184 higher interannual variability in many of the coastal states and more southern
185 catchments. We refer to other studies for a more extensive assessment of flood
186 seasonality [Hoyt and Langbein 1955; Villarini, 2016] and its connection with the
187 mean seasonal hydrologic conditions [Berghuijs et al., 2014b].

188

189 The $\bar{\Phi}$ - and σ_{Φ} -values of the four hypothesized flow predictors (maximum daily
190 precipitation, maximum weekly precipitation, precipitation excess, and snowmelt) all
191 show regional patterns, which are not the same for all processes (see Fig. 1b-e).
192 Maximum daily precipitation for the western coastal states generally falls during the
193 winter period and these maximum daily precipitation events rarely happen during
194 other times of the year. In the southeastern part of the US maximum daily
195 precipitation, on average, occurs during winter and early spring, but this date is more
196 variable. The other catchments have most maximum annual precipitation events
197 during the summer period, during late summer (northeast) and Fall (e.g. Arizona), but
198 regional differences exist in the temporal variability of this timing. Maximum weekly
199 precipitation gives a very similar pattern, but with some regional differences (e.g.
200 New Mexico and Florida). Precipitation excess is generally the highest during late
201 winter and early spring. Exceptions are the west coast (winter dominated), the mid-
202 west and some northeastern catchments. This date is not very variable between years
203 for western and central catchments, but on the east coast this variability increases.
204 Maximum snowmelt is only calculated for catchments with on average more than
205 10% of their precipitation falling as snow, which have maximum melt-rates at dates
206 ranging from early spring to early summer. These snowmelt or rain-on-snow events
207 are almost always during this part of the year.

208

209 Visual comparison of the $\bar{\Phi}$ -values (Fig. 1) already indicates that some predictors are
210 regionally highly unsuitable to describe when MAFs are occurring, and thus are not
211 the dominant processes for flood generation. In other regions or for other predictors
212 the correspondence is much better. Using scatter plots (Fig. 2) we highlight to what

213 degree the $\bar{\Phi}$ -values of flooding and predictors occur at the same time of the year. For
214 daily precipitation only a small fraction of catchments have a predicted date with a
215 reasonable correspondence to the observed flood date (Fig. 2a). The threshold is set at
216 35 days, but other time windows lead to comparable final results. For weekly
217 precipitation a similar pattern is observed with few catchments having their flood
218 timing well predicted by this mechanism. These results indicate that precipitation by
219 itself is a good predictor of flood seasonality only for a small fraction of the
220 catchments, suggesting that other processes play an important role. Many more
221 catchments show a reasonable correspondence between precipitation excess and flood
222 response. In general precipitation excess peaks slightly earlier in the year than
223 observed flood, but differences are within a few weeks, suggesting that precipitation
224 excess may be a more common control on flood generation. For most of the
225 catchments with a significant amount of snowfall, the date of maximum snowmelt and
226 rain-on-snow events is a good predictor for the timing of MAF.

227

228 **4.2 Interannual variability of floods and flood predictors**

229 The magnitude of MAF has differing degrees of interannual variability as the
230 coefficient of variation ($CV_Q = \text{std. dev. } (Q_{\text{MAF}}/\text{mean}(Q_{\text{MAF}}))$) varies among
231 catchments (Fig. 3a). The variability of annual flows is much larger for the central
232 more arid catchments, as already indicated by Guo et al., [2014] and is in line with the
233 finding of Farquharson et al. [1992] that the slope of the flood frequency curve
234 increases with aridity. To test which hypotheses provide explanations of the
235 interannual variability of flood magnitude, we quantify for individual catchments the
236 Spearman rank correlation between annual values of flood magnitude, and annual
237 values of hypothesized generating mechanisms. For catchments where multiple

mechanisms are still feasible according to the seasonality approximations (Fig. 2), we examine which process is able to explain most of the variability in the runoff (Fig. 3b), and show the associated Spearman rank correlation (Fig. 3c). The mechanism that is within 35 days of flood seasonality and that best explains the interannual variability in flood magnitude is identified as the dominant flood-generating mechanism.

The patterns of dominant flood-generating mechanisms indicate that different regions have different hydrological processes of importance. Daily and multi-day precipitation is a control of floods for many catchments in the central arid part of the United States. For the vast majority of catchments precipitation excess is the mechanism that can best reproduce both the timing and magnitude of maximum annual flows. Snow controls the flood response in the Rockies, and also in some of the other northern or high altitude catchments; for most of the catchments with a significant amount of snowfall, the maximum snowmelt and rain-on-snow events are within the same period of the year as the timing of MAF (Rocky Mountains, Sierra Nevada, Northern Cascades, northern part of Appalachian and the most northern located catchments). For a limited number of the catchments no single mechanism considered here is capable of reproducing the flood seasonality and no dominant mechanism is identified. Some of these catchments are located in regions with a uniform flood timing distribution [Villarini, 2016].

5. Discussion

5.1 On exposing controls of flood response

262 The top-down hypothesis testing to explain the seasonality of floods provides a
263 simple and repeatable (e.g. for other regions) method to decipher first order
264 understanding of the diverse nature of flood-generating mechanisms. Good
265 correspondence between the seasonality of MAF with only one process explanation
266 suggests that the proposed flood-generating mechanism is the primary control of
267 MAFs (Fig. 2). This is further substantiated by the Spearman rank correlation
268 coefficient that indicates the ability of the mechanisms to explain the interannual
269 variability in flood magnitude (Fig. 3c). Compared to other studies that use
270 seasonality to learn about the process controls on floods [e.g., Hirschboek, 1991;
271 Parajka et al., 2010; Villarini, 2016], our additional use of flood magnitude increases
272 the robustness and reduces the equifinality in identifying dominant mechanisms.

273

274 The strong disparity between the dates of maximum precipitation events and the date
275 of flooding is a simple but effective indicator that factors other than just precipitation
276 control the magnitude of floods over the United States. Although the process
277 explanations used here are extremely simplified, their first order differences in the
278 analysis indicate strong regional patterns in the controls of flood seasonality. With no
279 correspondence between maximum daily and weekly precipitation and flood response
280 in all but some central states, it must clearly be that other processes, e.g., snowmelt
281 and soil moisture, control the flood response across the majority of the United States.

282

283 In future work the flood-generating mechanisms can be refined further by expanding
284 the downward approach to hydrological prediction through modeling studies, which
285 can reflect the role of sub-daily flow dynamics, landscape properties, spatial
286 variability in more detail. The understanding presented here of regional patterns of

287 flood-generating mechanisms may also be expanded to more locations in the US,
288 including more human impacted environments, and can be extended to other
289 continents.

290

291 **5.2 Implications for flood prediction and trend analysis**

292 Although statistical approaches have played and will always play an important role in
293 flood estimation, they have to be complemented by the search for the causal
294 mechanisms and dominant processes in the atmosphere, catchment and river system
295 that leave their fingerprints on flood characteristics [Merz & Blöschl, 2008a,b; Merz
296 et al., 2014]. With the currently limited representation of process understanding in
297 continental scale US river flood studies [e.g., Lins & Slack, 1999; Villarini et al.,
298 2009; Hirsch & Ryberg, 2012], this study opens new pathways to better account for
299 the correct process controls and thereby improve flood estimation. The increased
300 likelihood of extreme rainfall under climate warming [Trenberth et al., 2003; Min et
301 al., 2011; Kendon et al., 2014] is projected to also lead to increases in the magnitude
302 and frequency of floods [Milly et al., 2002; Pall et al., 2011; Arnell & Gosling, 2014].
303 Although our results do not necessarily suggest that such predictions are not
304 representative, they indicate that for the majority of the soil moisture controlled
305 environments a more appropriate question is: how do changes in extreme precipitation
306 interact with soil water dynamics to alter precipitation excess events? This is
307 potentially one important reason why observed increases in precipitation extremes are
308 not reflected in historical flooding data [Ivancic & Shaw, 2015; Kundzewicz et al.,
309 2014; Lins & Slack, 1999; Villarini et al., 2009, 2011; Hirsch & Ryberg, 2012], but
310 when one focuses on the time of the year that such floods occur, distinct increases in
311 flood occurrence are observed [Mallakpour & Villarini, 2015]. Since the study only

312 highlights the primary controls of flood response, and the nature of seasonality and
313 process controls may change under changing climate and landscape condition,
314 especially in snowy regions [Regonda et al., 2005; Köplin et al, 2014] and regions
315 that urbanize [Ashley et al., 2005], the nature of flooding may strongly shift.

316

317 **6. Conclusions**

318 We highlight strong regional differences in the time of the year that MAFs have
319 occurred across the contiguous United States. By combining this flood statistic with
320 potential process explanations we highlight strong regional patterns in some of the
321 mechanisms that may be controlling MAF. Flood seasonality is, in general, explained
322 poorly by extreme rainfall seasonality; only for the central arid part of the USA is
323 flood seasonality controlled by extreme precipitation events. Evaporation controlled
324 soil moisture plays a dominant role for the majority of catchments, while for
325 catchments with much snow the timing of MAF is primarily controlled by snow
326 dynamics. This disparity between extreme flows and extreme rainfall is also reflected
327 in the interannual variability of the magnitude of MAF; the interannual variability of
328 MAF is poorly explained by precipitation variability; whereas the variability of
329 evaporation and soil moisture-controlled precipitation excess explains more of the
330 MAF variability. This suggests that across large parts of the USA including now
331 readily available information on hydrological processes can strengthen the
332 relationships between statistical characteristics of extreme precipitation and extreme
333 floods.

334

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337 data sets are available via: ftp://hydrology.nws.noaa.gov/pub/gcip/mopex/US_Data/
338

339 **References**

- 340 1. Allan, R. P., & Soden, B. J. (2008). Atmospheric warming and the amplification
341 of precipitation extremes. *Science*, 321(5895), 1481-1484, doi:
342 10.1126/science.1160787
- 343 2. Arnell, N. W., & Gosling, S. N. (2014). The impacts of climate change on river
344 flood risk at the global scale. *Climate Change*, 1-15, doi:10.1007/s10584-014-
345 1084-5
- 346 3. Ashley, S. T., & Ashley, W. S. (2008). Flood fatalities in the United States.
347 *Journal of Applied Meteorology and Climatology*, 47(3), 805-818, doi:
348 10.1175/2007JAMC1611.1
- 349 4. Ashley, R., Balmforth, D., Saul, A., & Blanskby, J. (2005). Flooding in the future
350 predicting climate change, risks and responses in urban areas. *Water Science &*
351 *Technology*, 52(5), 265-273.
- 352 5. Berghuijs, W. R., Woods, R. A., & Hrachowitz, M. (2014a). A precipitation shift
353 from snow towards rain leads to a decrease in streamflow. *Nature Climate*
354 *Change*, 4(7), 583-586, doi:10.1038/nclimate2246
- 355 6. Berghuijs, W. R., M. Sivapalan, R. A. Woods, and H. H. G. Savenije (2014b),
356 Patterns of similarity of seasonal water balances: A window into streamflow
357 variability over a range of time scales, *Water Resources Research*, 50, 5638–5661,
358 doi: 10.1002/2014WR015692.
- 359 7. Bradshaw, C. J., Sodhi, N. S., Peh, K. S. H., & Brook, B. W. (2007), Global
360 evidence that deforestation amplifies flood risk and severity in the developing
361 world. *Global Change Biology*, 13: 2379–2395. doi: 10.1111/j.1365-
362 2486.2007.01446.x

- 363 8. Burn, D. (1997), Catchment similarity for regional flood frequency analysis using
364 seasonality measures. *Journal of Hydrology*, 202 (2), 12–230, doi:10.1016/S0022-
365 1694(97)00068-1
- 366 9. Cunnane, C. (1988). Methods and merits of regional flood frequency analysis.
367 *Journal of Hydrology*, 100(1), 269-290, doi:10.1016/0022-1694(88)90188-6
- 368 10. Cunderlik, J. M., T. B. M. J. Ouarda, and B. Bobée (2004), On the objective
369 identification of flood seasons, *Water Resources Research*, 40, W01520,
370 doi:10.1029/2003WR002295.
- 371 11. Di Baldassarre, G., Montanari, A., Lins, H., Koutsoyiannis, D., Brandimarte, L.,
372 & Blöschl, G. (2010). Flood fatalities in Africa: from diagnosis to mitigation.
373 *Geophysical Research Letters*, 37(22), doi:10.1029/2010GL045467
- 374 12. Duan, Q., Schaake, J., Andreassian, V., Franks, S., Goteti, G., Gupta, H. V., ... &
375 Wood, E. F. (2006). Model Parameter Estimation Experiment (MOPEX): An
376 overview of science strategy and major results from the second and third
377 workshops. *Journal of Hydrology*, 320(1), 3-17,
378 doi:10.1016/j.jhydrol.2005.07.031
- 379 13. Dunne, T. (1978), Field studies of hillslope flow processes. In: Kirkby, M.J. (Ed.),
380 Hillslope Hydrology. Wiley-Interscience, New York, pp. 227–293.
- 381 14. Farquharson, F. A. K., J. R. Meigh, and J. V. Sutcliffe (1992), Regional flood
382 frequency analysis in arid and semi-arid areas, *Journal of Hydrology*, 138(3–4),
383 487–501, doi:10.1016/0022-1694(92)90132-F
- 384 15. Freudiger, D., Kohn, I., Stahl, K., and Weiler, M. (2014). Large-scale analysis of
385 changing frequencies of rain-on-snow events with flood-generation potential,
386 *Hydrol. Earth Syst. Sci.*, 18, 2695-2709, doi:10.5194/hess-18-2695-2014.

- 387 16. Gao, H., Hrachowitz, M., Schymanski, S. J., Fenicia, F., Sriwongsitanon, N., &
388 Savenije, H. H. G. (2014). Climate controls how ecosystems size the root zone
389 storage capacity at catchment scale. *Geophysical Research Letters*, 41(22), 7916-
390 7923, doi: 10.1002/2014GL061668
- 391 17. Groisman, P. Y., Knight, R. W., Easterling, D. R., Karl, T. R., Hegerl, G. C., &
392 Razuvaev, V. N. (2005). Trends in intense precipitation in the climate record.
393 *Journal of Climate*, 18(9), 1326-1350, doi: <http://dx.doi.org/10.1175/JCLI3339.1>
- 394 18. Gumbel, E. J. (1941). The return period of flood flows. *The Annals of*
395 *Mathematical Statistics*, 12(2), 163-190.
- 396 19. Guo, J., H.-Y. Li, L. R. Leung, S. Guo, P. Liu, and M. Sivapalan (2014). Links
397 between flood frequency and annual water balance behaviors: A basis for
398 similarity and regionalization, *Water Resources Research*, 50, 937-953,
399 doi:10.1002/2013WR014374.
- 400 20. Hirsch, R.M., and Ryberg, K.R. (2012). Has the magnitude of floods across the
401 USA changed with global CO2 levels? *Hydrological Sciences Journal*, 57 (1), 1-
402 9, doi: 10.1080/02626667.2011.621895
- 403 21. Hirschboeck, K.K., 1991. Climate and floods. In Paulson, R.W., Chase, E.B.,
404 Moody, D.W. (Eds.). National Water Summary 1988-89, Floods and Droughts,
405 US Geol. Surv. Water-Supply, Pap. 2375
- 406 22. Hock, R. (2003). Temperature index melt modelling in mountain areas. *Journal of*
407 *Hydrology*, 282(1), 104-115, doi:10.1016/S0022-1694(03)00257-9
- 408 23. Hoyt, W.G., and Langbein, W.B. (1955). Floods. Princeton University Press,
409 469pp

- 410 24. Ivancic, T.J., and. Shaw, S.B. (2015). Examining why trends in very heavy
411 precipitation should not be mistaken for trends in very high river discharge,
412 *Climatic Change*, 133(4), 681-693, doi: 10.1007/s10584-015-1476-1
- 413 25. Jongman, B., Ward, P. J., & Aerts, J. C. (2012). Global exposure to river and
414 coastal flooding: Long term trends and changes. *Global Environmental Change*,
415 22(4), 823-835, doi:10.1016/j.gloenvcha.2012.07.004
- 416 26. Kendon, E. J., Roberts, N. M., Fowler, H. J., Roberts, M. J., Chan, S. C., &
417 Senior, C. A. (2014). Heavier summer downpours with climate change revealed
418 by weather forecast resolution model. *Nature Climate Change*, 4, 570–576,
419 doi:10.1038/nclimate2258
- 420 27. Klemeš, V. (1983). Conceptualization and scale in hydrology. *Journal of*
421 *Hydrology*, 65(1), 1-23, doi:10.1016/0022-1694(83)90208-1
- 422 28. Köplin, N., Schädler, B., Viviroli, D., & Weingartner, R. (2014). Seasonality and
423 magnitude of floods in Switzerland under future climate change. *Hydrological*
424 *Processes*, 28(4), 2567-2578, doi: 10.1002/hyp.9757
- 425 29. Kundzewicz, Z. W., et al. (2014), Flood risk and climate change: Global and
426 regional perspectives, *Hydrological Sciences Journal*, 59(1), 1– 28,
427 doi:10.1080/02626667.2013.857411.
- 428 30. Lins, H. F., & Slack, J. R. (1999). Streamflow trends in the United States.
429 *Geophysical Research Letters*, 26(2), 227-230, doi: 10.1029/1998GL900291
- 430 31. Mallakpour, I., & Villarini, G. (2015), The changing nature of flooding across the
431 central United States, *Nature Climate Change*, 5(3), 250–254,
432 doi:10.1038/nclimate2516.

- 433 32. McCabe, G. J., Hay, L. E., & Clark, M. P. (2007). Rain-on-snow events in the
434 western United States. *Bulletin of the American Meteorological Society*, 88(3),
435 319-328, doi: <http://dx.doi.org/10.1175/BAMS-88-3-319>
- 436 33. Merz, R., U. Piock-Ellena, G. Blöschl, and D. Gutknecht (1999), Seasonality of
437 flood processes in Austria, in *Hydrological Extremes: Understanding, Predicting,*
438 *Mitigating*, edited by L. Gottschalk et al., *IAHS Publ.*, 255, 273–278.
- 439 34. Merz, R. and G. Blöschl (2003), A process typology of regional floods, *Water*
440 *Resources Research*, 39(12), 1340, doi:10.1029/2002WR001952.
- 441 35. Merz, R., and G. Blöschl (2008a), Flood frequency hydrology: 1. Temporal,
442 spatial, and causal expansion of information, *Water Resources Research*, 44,
443 W08432, doi:10.1029/2007WR006744.
- 444 36. Merz, R., and G. Blöschl (2008b), Flood frequency hydrology: 2. Combining data
445 evidence, *Water Resources Research*, 44, W08433, doi:10.1029/2007WR006745.
- 446 37. Merz, R., and G. Blöschl (2008c), Process controls on the statistical flood
447 moments—A data based analysis, *Hydrological Processes*, 23(5), 675– 696, doi:
448 10.1002/hyp.7168
- 449 38. Merz, B., Aerts, J., Arnbjerg-Nielsen, K., Baldi, M., Becker, A., Bichet, A., ... &
450 Nied, M. (2014). Floods and climate: emerging perspectives for flood risk
451 assessment and management. *Natural Hazards and Earth System Sciences*, 14(7),
452 1921-1942, doi:10.5194/nhess-14-1921-2014
- 453 39. Milly, P. C. D. (1994). Climate, interseasonal storage of soil water, and the annual
454 water balance. *Advances in Water Resources*, 17(1), 19-24, doi:10.1016/0309-
455 1708(94)90020-5,

- 456 40. Milly, P. C. D., Wetherald, R., Dunne, K. A., & Delworth, T. L. (2002).
457 Increasing risk of great floods in a changing climate. *Nature*, 415(6871), 514-517,
458 doi:10.1038/415514a
- 459 41. Milly, P. C. D. et al. (2008). Stationarity is dead: Whither water management?
460 *Science*, 319, 573-574, doi: 10.1126/science.1151915
- 461 42. Min, S-K., Zhang, X., Zwiers, F. W. & Hegerl, G. C. (2011). Human contribution
462 to more-intense precipitation extremes. *Nature*, 470, 376-379,
463 doi:10.1038/nature09763
- 464 43. Pall, P., Aina, T., Stone, D. A., Stott, P. A., Nozawa, T., Hilberts, A. G., ... &
465 Allen, M. R. (2011). Anthropogenic greenhouse gas contribution to flood risk in
466 England and Wales in autumn 2000. *Nature*, 470(7334), 382-385,
467 doi:10.1038/nature09762
- 468 44. Parajka, J., Kohnová, S., Bálint, G., Barbuc, M., Borga, M., Claps, P., ... &
469 Blöschl, G. (2010). Seasonal characteristics of flood regimes across the Alpine-
470 Carpathian range. *Journal of hydrology*, 394(1), 78-89,
471 doi:10.1016/j.jhydrol.2010.05.015
- 472 45. Regonda, S. K., Rajagopalan, B., Clark, M., & Pitlick, J. (2005). Seasonal cycle
473 shifts in hydroclimatology over the western United States. *Journal of Climate*,
474 18(2), 372-384, doi: <http://dx.doi.org/10.1175/JCLI-3272.1>
- 475 46. Richter, B. D., & Thomas, G. A. (2007). Restoring environmental flows by
476 modifying dam operations. *Ecology and society*, 12(1), 12.
- 477 47. Šimůnek, J., Jarvis, N. J., Van Genuchten, M. T., & Gärdenäs, A. (2003). Review
478 and comparison of models for describing non-equilibrium and preferential flow
479 and transport in the vadose zone. *Journal of Hydrology*, 272(1), 14-35,
480 doi:10.1016/S0022-1694(02)00252-4

- 481 48. Sivapalan, M., Blöschl, G., Zhang, L., & Vertessy, R. (2003). Downward
482 approach to hydrological prediction. *Hydrological processes*, 17(11), 2101-2111,
483 doi: 10.1002/hyp.1425
- 484 49. Sivapalan, M., G. Blöschl, R. Merz, and D. Gutknecht (2005), Linking flood
485 frequency to long-term water balance: Incorporating effects of seasonality, *Water*
486 *Resourch Research*, 41, W06012, doi:10.1029/2004WR003439.
- 487 50. Slater, L. J., M. B. Singer, and J. W. Kirchner (2015), Hydrologic versus
488 geomorphic drivers of trends in flood hazard, *Geophysical Research Letters*, 42,
489 370–376, doi:10.1002/2014GL062482.
- 490 51. Smith, A., Sampson, C., & Bates, P. (2015). Regional flood frequency analysis at
491 the global scale. *Water Resources Research*, 51(1), 539-553, doi:
492 10.1002/2014WR015814.
- 493 52. Te Linde, A. H., Bubeck, P., Dekkers, J. E. C., De Moel, H., & Aerts, J. C. J. H.
494 (2011). Future flood risk estimates along the river Rhine. *Natural Hazards and*
495 *Earth System Sciences*, 11, 459-473, doi:10.5194/nhess-11-459-2011
- 496 53. Tromp-van Meerveld, H. J., and J. J. McDonnell (2006), Threshold relations in
497 subsurface stormflow: 2. The fill and spill hypothesis, *Water Resources Research*,
498 42, W02411, doi:10.1029/2004WR003800.
- 499 54. Thomaz, S. M., Bini, L. M., & Bozelli, R. L. (2007). Floods increase similarity
500 among aquatic habitats in river-floodplain systems. *Hydrobiologia*, 579(1), 1-13,
501 doi: 10.1007/s10750-006-0285-y
- 502 55. Trenberth, K. E., Dai, A., Rasmussen, R. M. & Parsons, D. B. (2003). The
503 changing character of precipitation. *Bulletin of the American Meteorological*
504 *Society*, 84, 1205–1217, doi: <http://dx.doi.org/10.1175/BAMS-84-9-1205>

- 505 56. Villarini, G., F. Serinaldi, J. A. Smith, and W. F. Krajewski (2009), On the
506 stationarity of annual flood peaks in the continental United States during the 20th
507 century, *Water Resources Research*, 45, W08417, doi:10.1029/2008WR007645.
- 508 57. Villarini, G., and J. A. Smith (2010), Flood peak distributions for the eastern
509 United States, *Water Resources Research*, 46, W06504,
510 doi:10.1029/2009WR008395.
- 511 58. Villarini, G., Smith, J. A., Baek, M. L. and Krajewski, W. F. (2011), Examining
512 Flood Frequency Distributions in the Midwest U.S.. *JAWRA Journal of the*
513 *American Water Resources Association*, 47, 447–463. doi: 10.1111/j.1752-
514 1688.2011.00540.x
- 515 59. Villarini, G. (2016). On the Seasonality of Flooding Across the Continental
516 United States. *Advances in Water Resources*, 87, 80-91,
517 doi:10.1016/j.advwatres.2015.11.009
- 518 60. Wang, D., and M. Hejazi (2011), Quantifying the relative contribution of the
519 climate and direct human impacts on mean annual streamflow in the contiguous
520 United States, *Water Resources Research*, 47, W00J12,
521 doi:10.1029/2010WR010283.
- 522 61. Westra, S., Alexander, L. V., & Zwiers, F. W. (2013). Global increasing trends in
523 annual maximum daily precipitation. *Journal of Climate*, 26(11), 3904-3918, doi:
524 <http://dx.doi.org/10.1175/JCLI-D-12-00502.1>
- 525 62. Winsemius, H. C., Aerts, J. C., van Beek, L. P., Bierkens, M. F., Bouwman, A.,
526 Jongman, B., ... & Ward, P. J. (2015). Global drivers of future river flood risk.
527 *Nature Climate Change*, advance online publication, doi:10.1038/nclimate2893

- 528 63. Woods, R. A. (2009). Analytical model of seasonal climate impacts on snow
529 hydrology: Continuous snowpacks. *Advances in water resources*, 32(10), 1465-
530 1481, doi:10.1016/j.advwatres.2009.06.011
- 531 64. Young, A. R., Round, C. E., & Gustard, A. (2000), Spatial and temporal
532 variations in the occurrence of low flow events in the UK, *Hydrol. Earth Syst.*
533 *Sci.*, 4, 35-45, doi:10.5194/hess-4-35-2000
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535 **List of Figures**

536

537 **Figure 1:** Mean day of (a) maximum annual daily flow, (b) maximum daily
538 precipitation, (c) maximum weekly precipitation, (d) maximum precipitation excess,
539 and (e) maximum snowmelt and associated standard deviations (right column). Black
540 crosses indicate that the data were not calculated due to an absence of significant
541 snow (<10% of total precipitation).

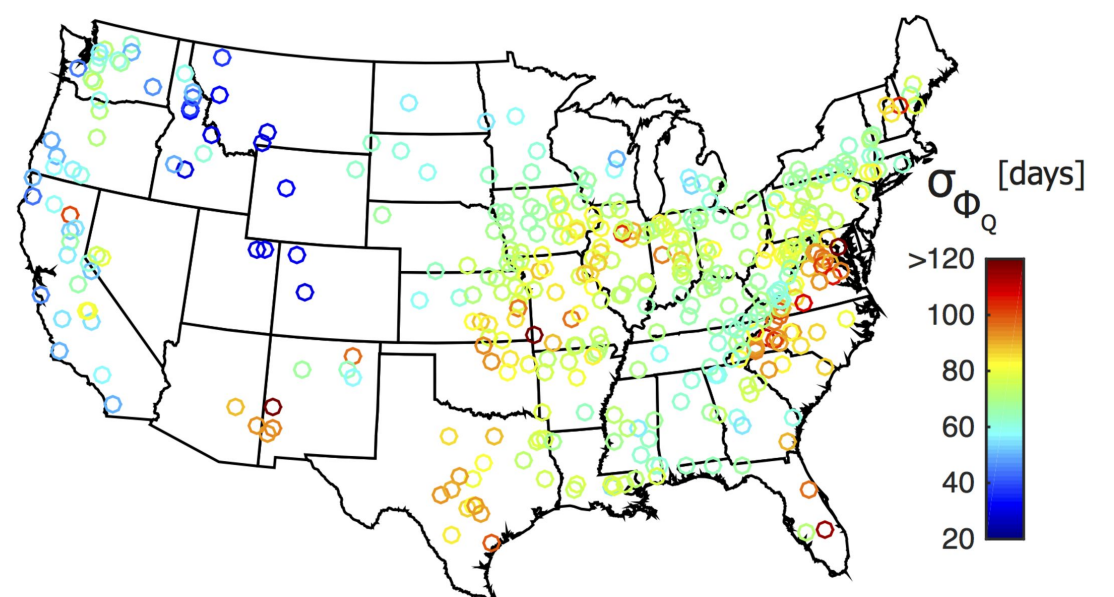
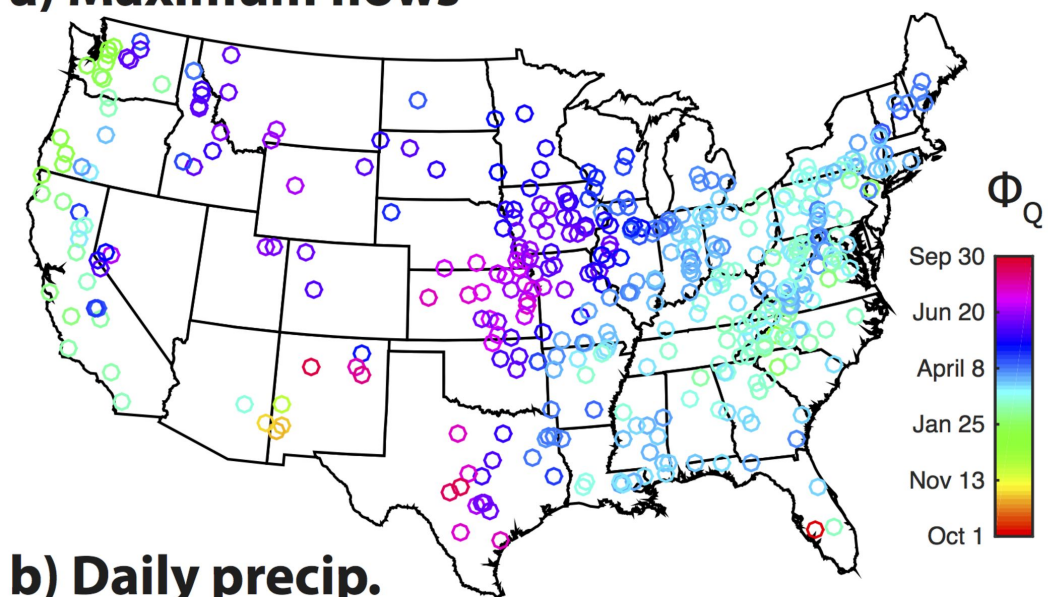
542

543 **Figure 2:** Correspondence of predictors of maximum annual flow and the mean day
544 of maximum annual daily flow as indicated by scatterplots with the 35 days
545 hypothesis rejection limit and the spatial occurrence of rejected (black symbols) and
546 plausible (colored symbols) hypotheses. The number of catchments that fall within
547 the rejection limit varies per mechanism: maximum daily precipitation (109/420),
548 maximum weekly precipitation (122/420), precipitation excess (249/420), and
549 snowmelt (155/420).

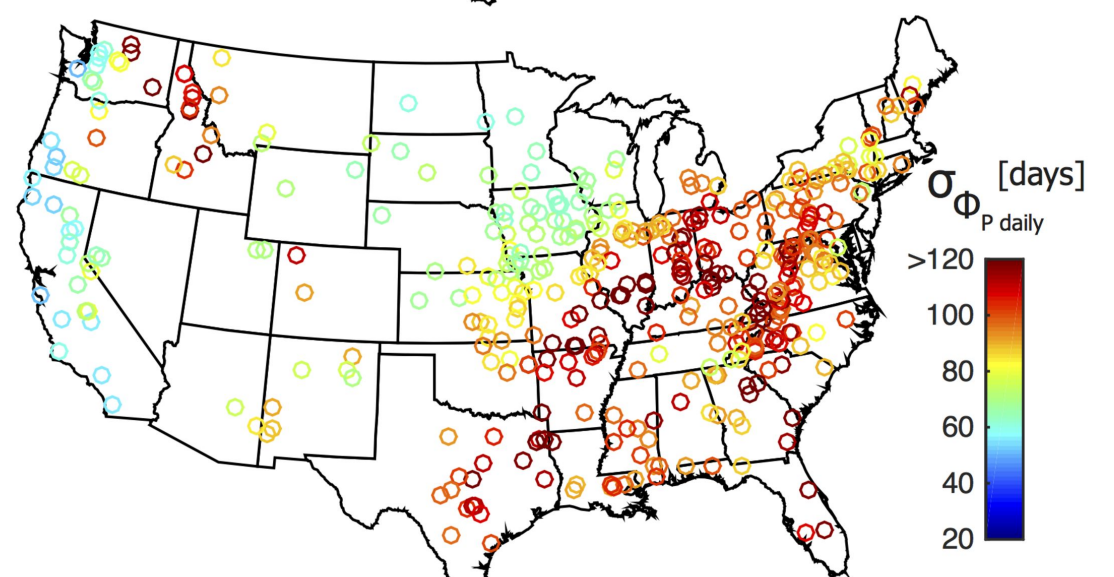
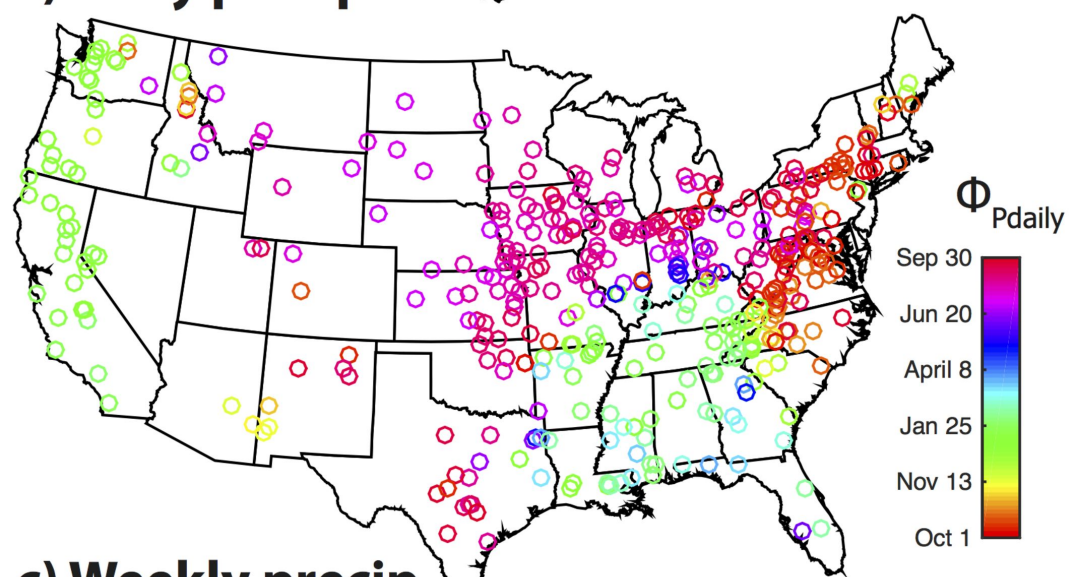
550

551 **Figure 3:** (a) Coefficient of variability of annual maximum flow (CV_Q), (b) the
552 mechanism that explains most variability in the runoff magnitude (based on highest
553 Spearman rank correlation coefficient), and (c) the associated interannual variability
554 explained as expressed by the Spearman rank correlation coefficient. Black crosses
555 indicate that all mechanisms were already rejected in the seasonality analysis.

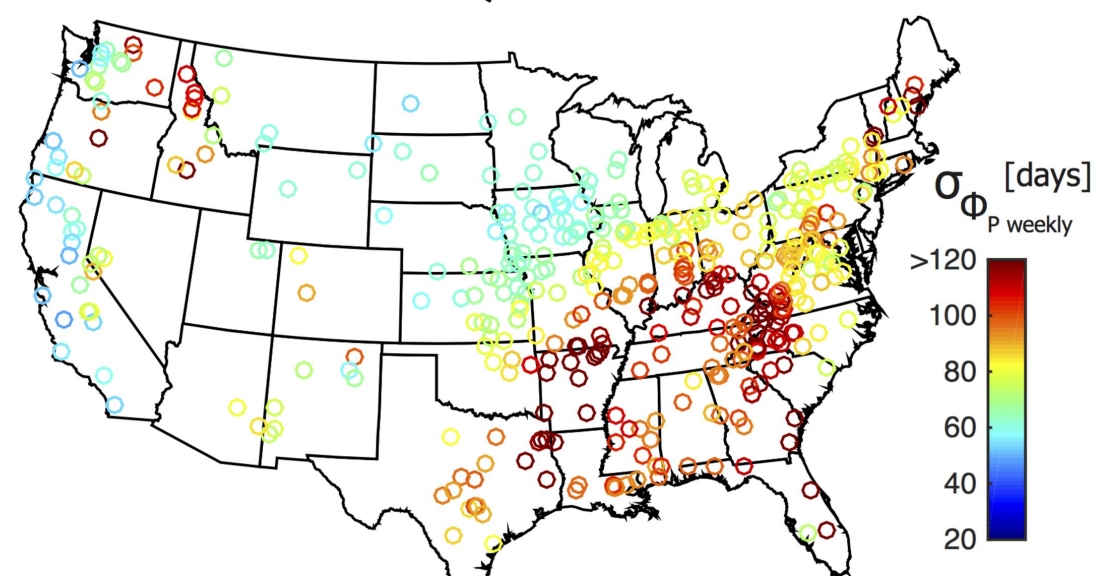
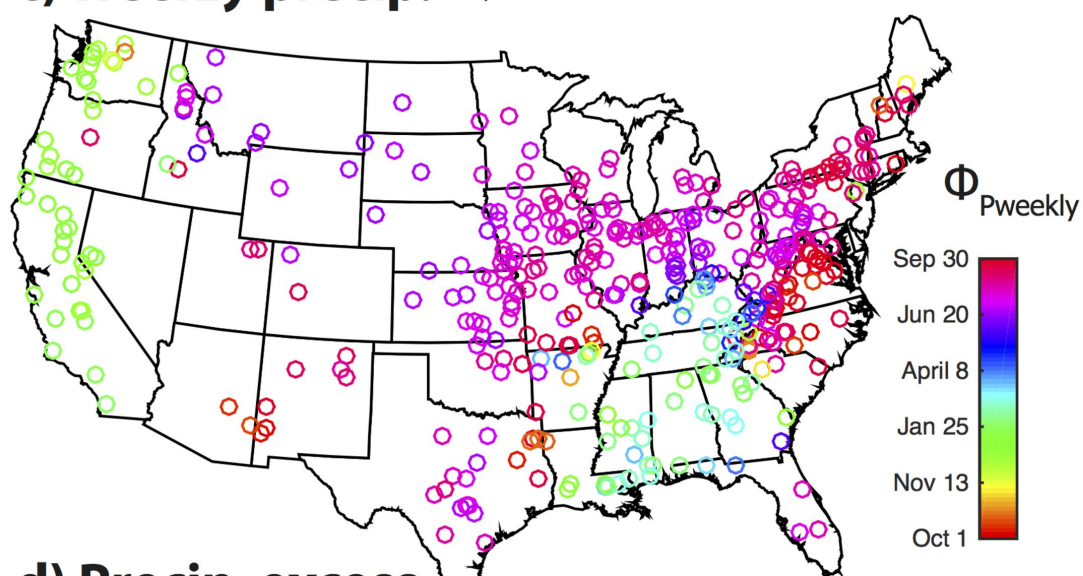
a) Maximum flows



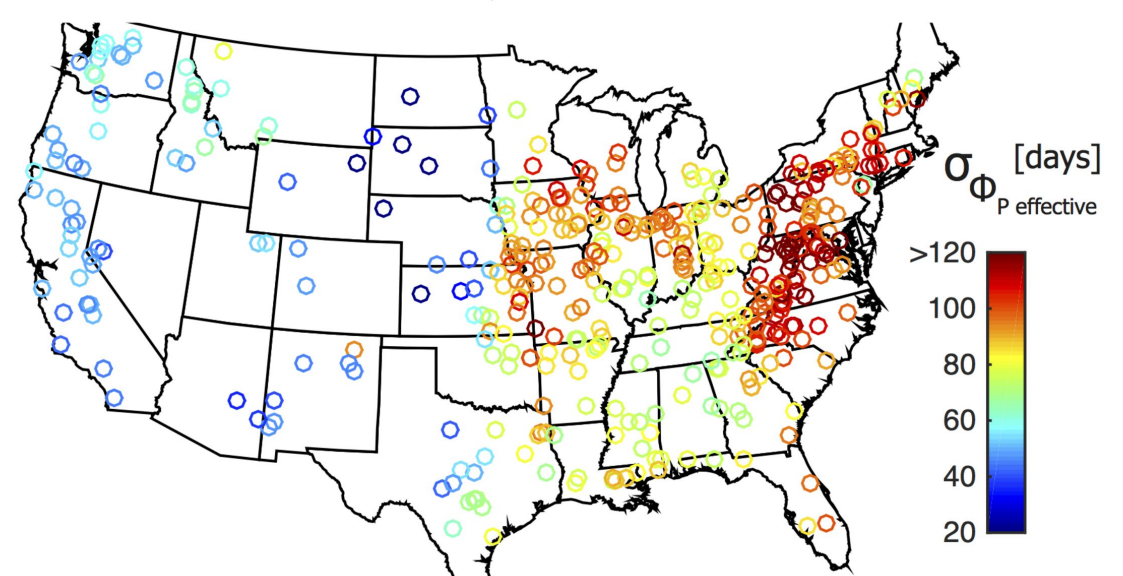
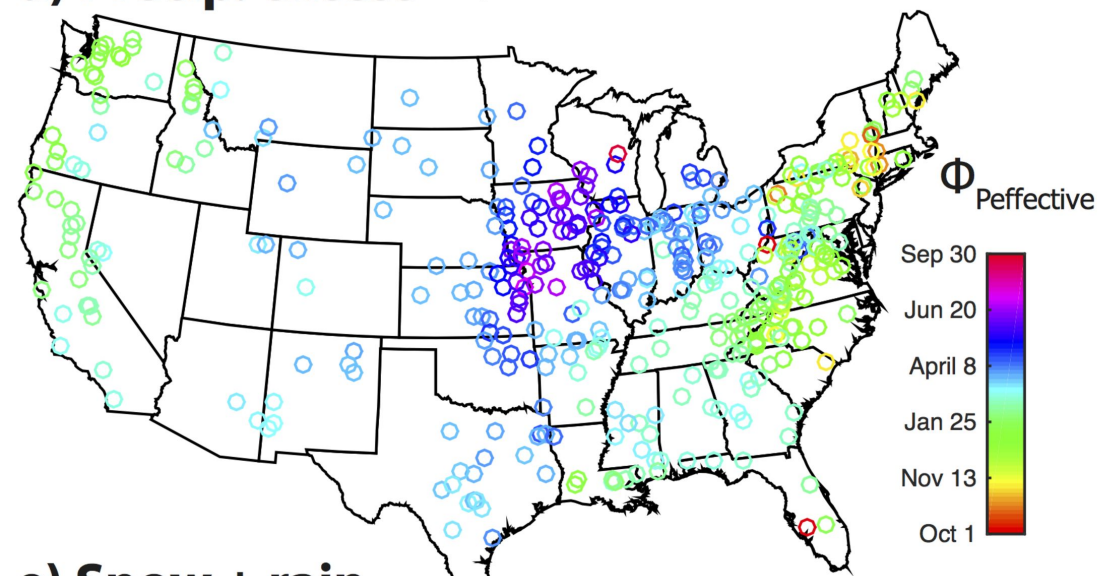
b) Daily precip.



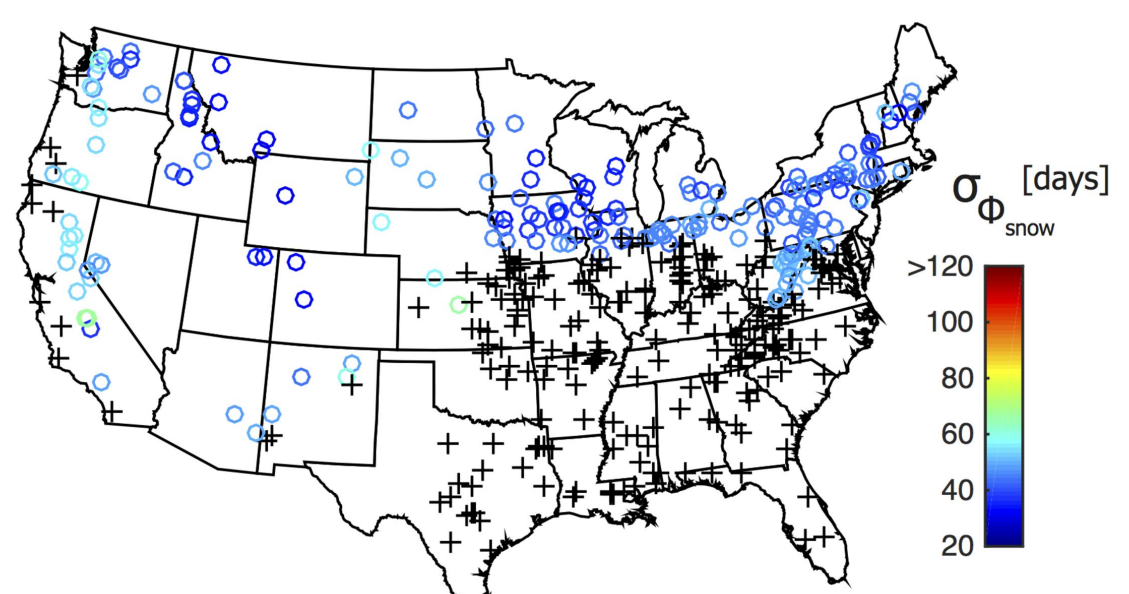
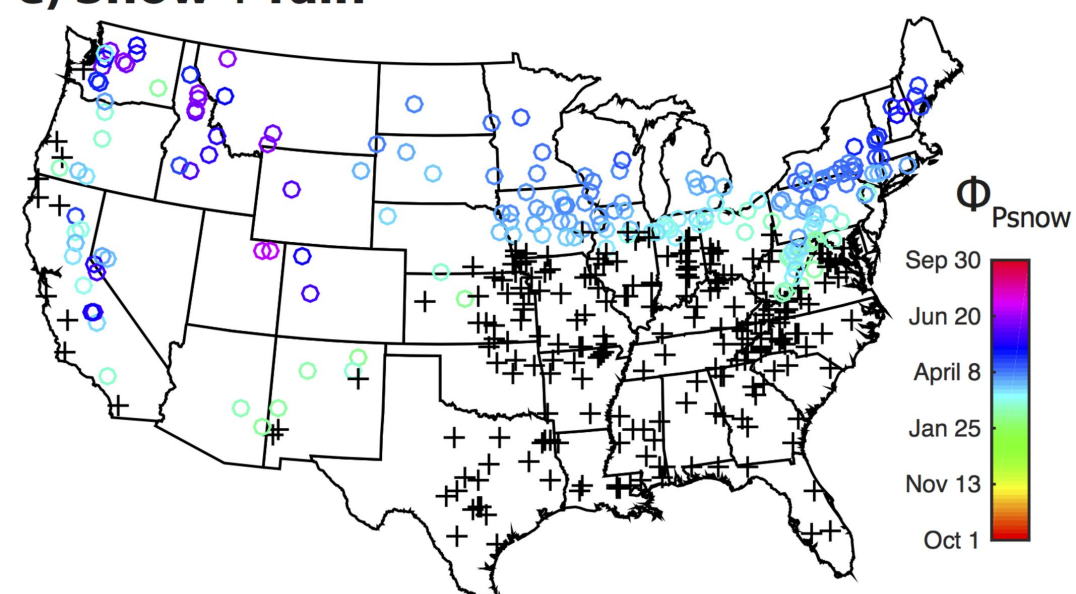
c) Weekly precip.



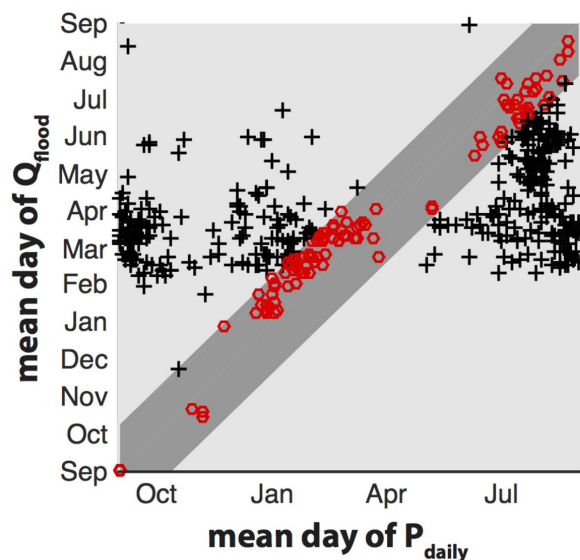
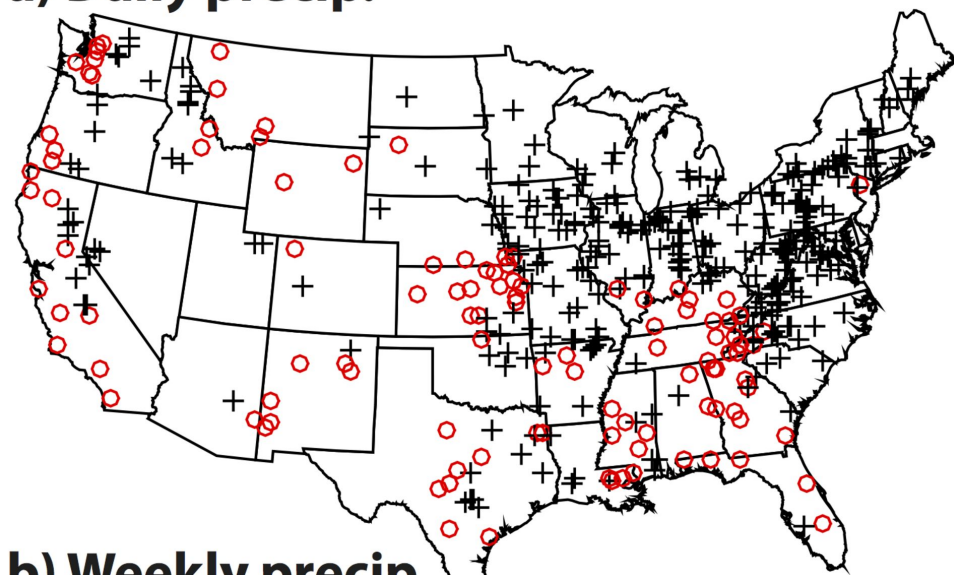
d) Precip. excess



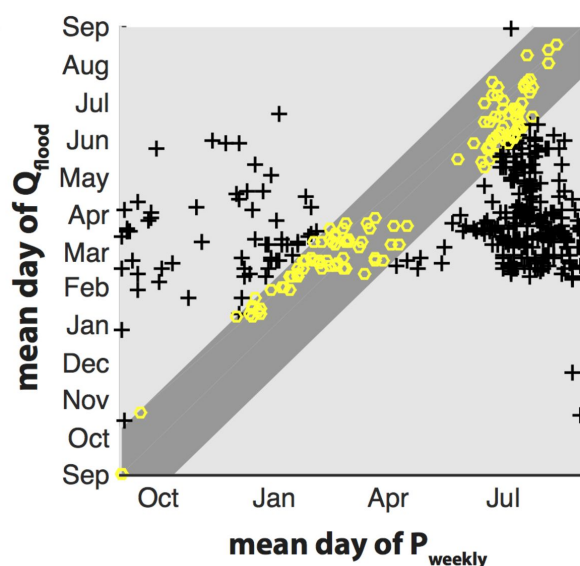
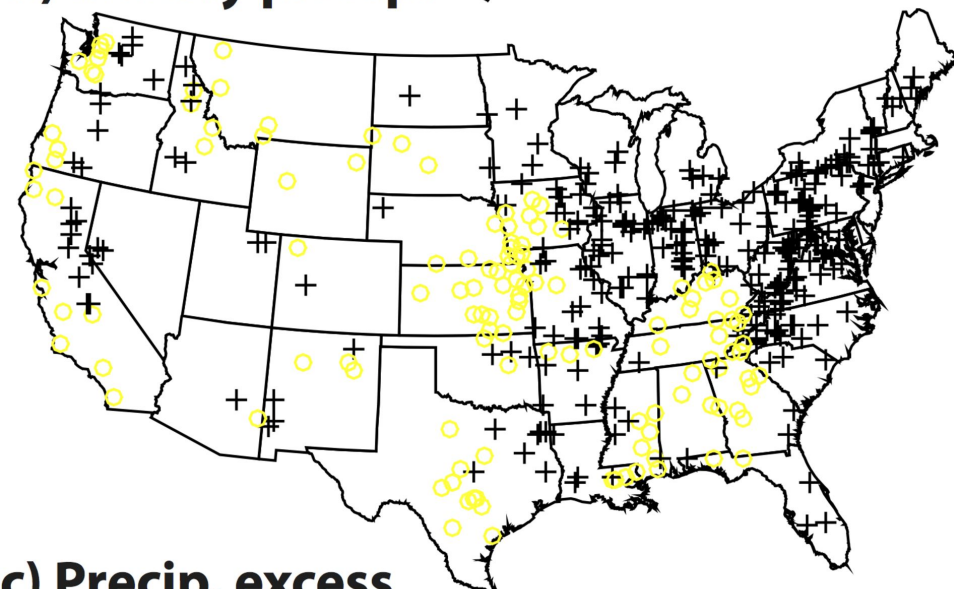
e) Snow + rain



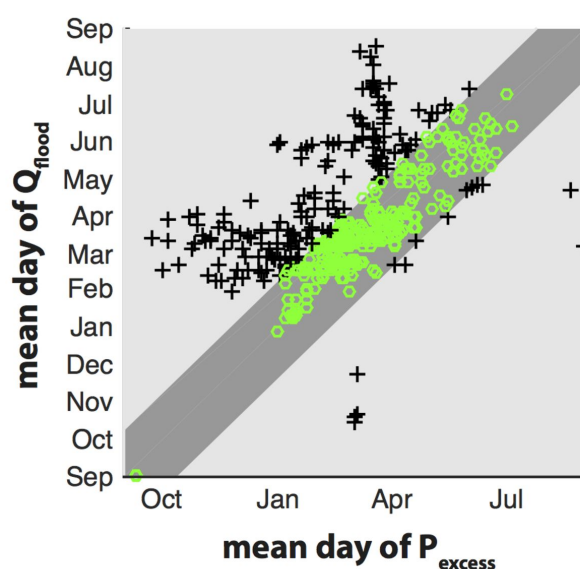
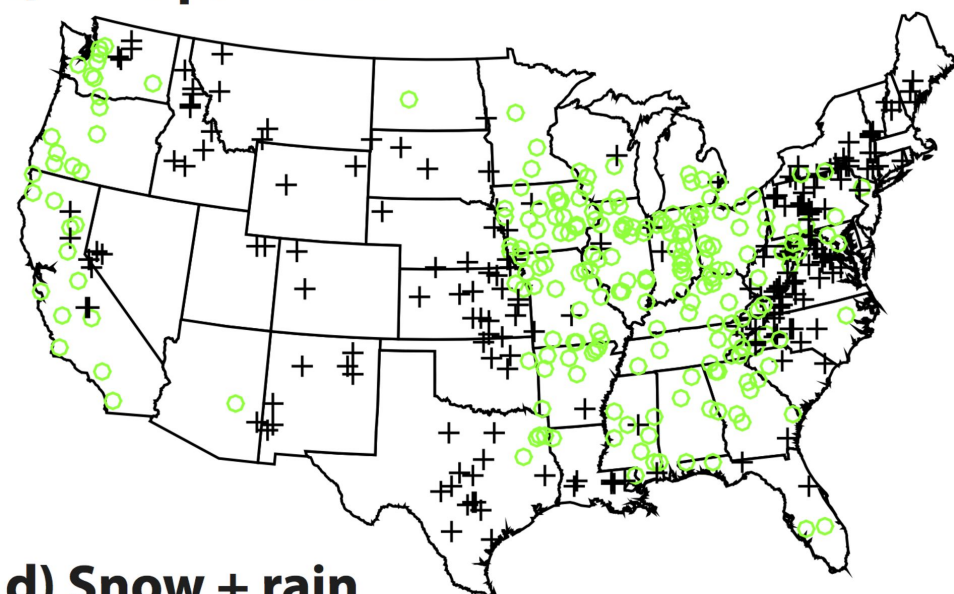
a) Daily precip.



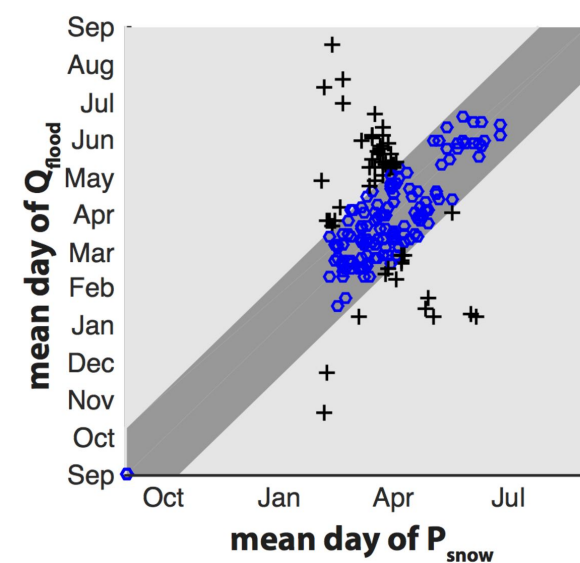
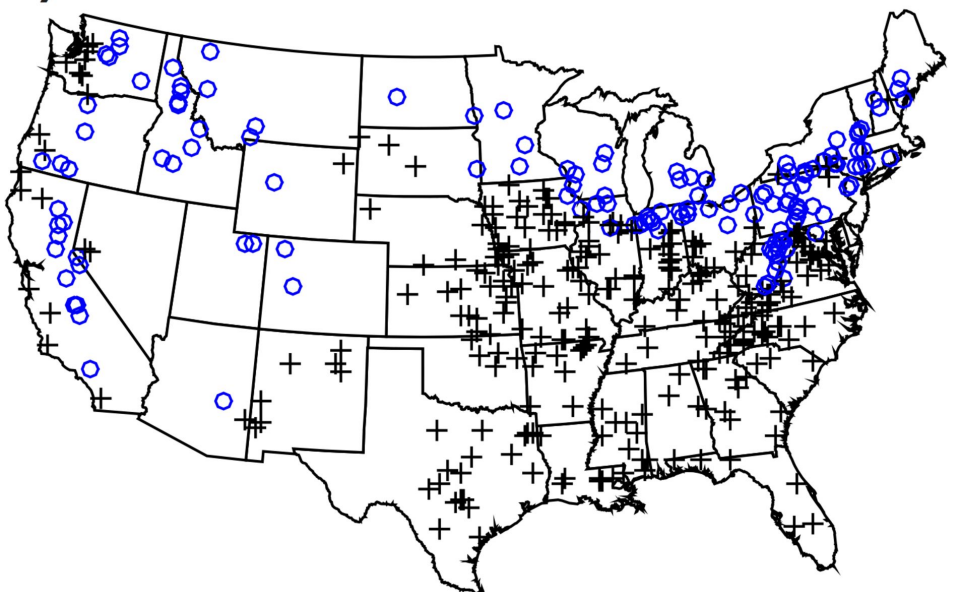
b) Weekly precip.



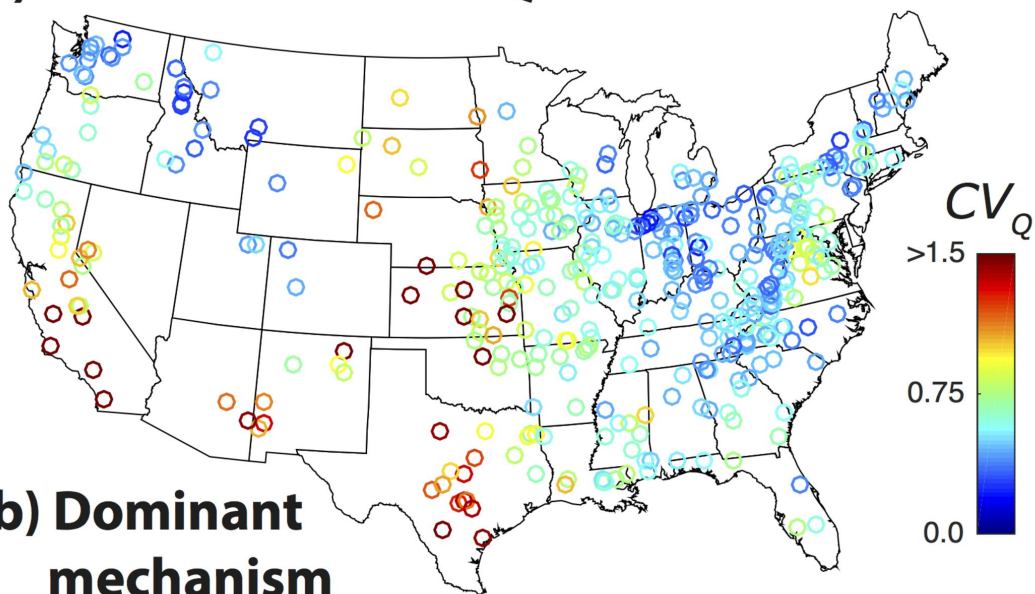
c) Precip. excess



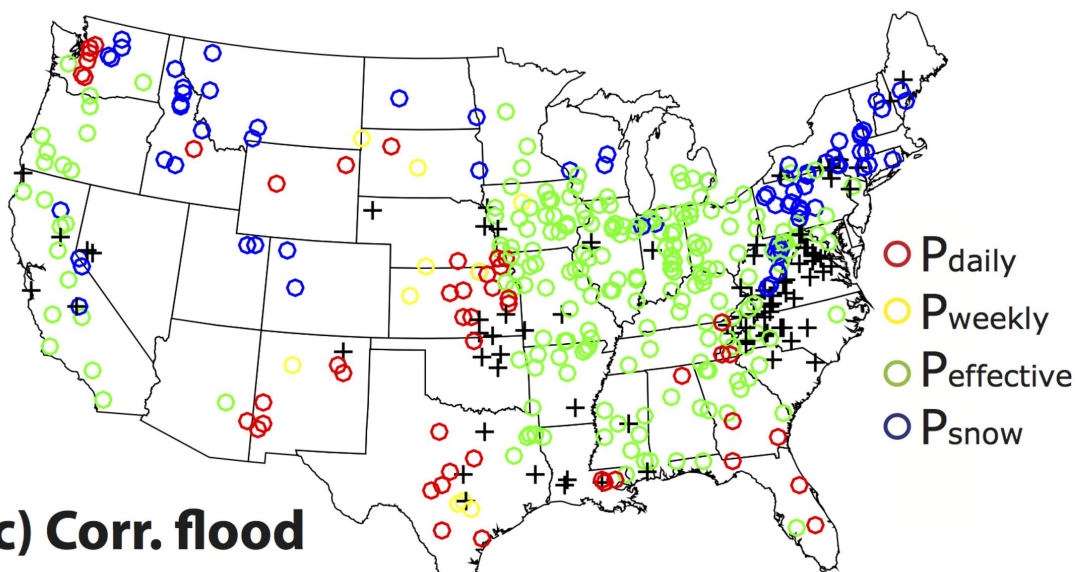
d) Snow + rain



a) Coeff. of variation Q



b) Dominant mechanism



c) Corr. flood and mechanism

